

**EXPLOSION SOURCE PHENOMENA USING SOVIET TEST ERA WAVEFORM DATA**

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**ABSTRACT**

During the nuclear testing era, the former Soviet Union carried out extensive observations of underground nuclear explosions, recording both their own shots and those of foreign nuclear states. Between 1961 and 1989, the Soviet “Complex Seismological Expedition” deployed seismometers at time-varying subsets of over 150 sites to record explosions at regional distances from the Semipalatinsk and Lop Nor test sites and from the shot points of peaceful nuclear explosions. This data set included recordings from broadband, multi-channel ChISS<sup>1</sup> seismometers that produced a series of band-limited outputs, which could then be measured to perform spectral studies. Quantitative, pre-digital era investigations of high-frequency source scaling relied on this type of data (e.g., Aki and Chouet, 1975; Rautian and Khalturin, 1978; Tsujiura, 1978). To augment data sets of Central Asia explosions, we have measured and compiled ChISS coda envelopes for Semipalatinsk events recorded at Talgar, now Kazakhstan. In addition, we have compiled regional, direct phase measurements for ChISS recordings at Talgar, Garm, Zerenda, and Novosibirsk. The Talgar coda data were used to construct an average scaling law of coda spectra for Semipalatinsk explosions, presented in last year’s contribution. The ChISS envelope data have been integrated into coda processing at Los Alamos National Laboratory (LANL) by applying ChISS filter bands to modern, digital data from central and east Asia, for purposes of yield calibration. The difference in manual versus digital measurement methods are captured in site terms that are higher by up to 0.5 log<sub>10</sub> units for ChISS data, relative to modern Talgar data due to the measurement of peak, rather than mean envelopes. After correction for site and path effects, ChISS amplitudes compare well to measurements from the Borovoye archive for events in common. Direct wave measurements have been used to construct spectra for Semipalatinsk explosions, and will be used to explore the behavior of regional phase amplitudes with shot point and emplacement condition. For example, we see a marked difference in the complexity of P phases, quantified by P<sub>n</sub>/P<sub>2</sub> ratios, where P<sub>2</sub> is a secondary P phase, between Balapan and Degelen source regions.

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<sup>1</sup> ChISS is the Russian abbreviation for multichannel spectral seismometer. In this instrument the signal from the seismometer is passed through a system of bandpass filters and recorded on photo paper. ChISS instruments have from 8 to 16 channels in the frequency range from 100 sec to 40 Hz. We used data mostly from 8 channel instruments in the range of 0.3 to 40 Hz.

**OBJECTIVE**

Our objective is to augment the collection of seismic recordings of central Asia underground nuclear tests and test-site earthquakes using ChISS data collected between 1961 and 1989, and to integrate these data into processing schemes currently in use with modern digital data. This will greatly increase the numbers of events used in explosion source scaling, yield estimation, and event identification studies.

**RESEARCH ACCOMPLISHED**

**1. The ChISS Instrument**

The ChISS instrument is a real-time, spectral-analyzing seismic recording system, designed by K.K. Zapolsky in the early 1950s. It produced band-passed traces in several (usually 7-10) frequency channels over a broad range from 100 sec to 40 Hz.

Any description of signal in the time domain, and its frequency content, is limited by an uncertainty principle that relates the time interval  $dt$  over which a frequency component  $f_0$  endures in the time domain to a frequency band of width  $df$  (centered on  $f_0$ ) within which the Fourier spectrum has significant amplitude in the frequency domain:  $df$  is inversely proportional to  $dt$ . If we want an accurate measure of the strength of the  $f_0$  component, it appears we need a long time interval,  $dt$ , in order to have a small value of  $df$ . Although this gives detailed information on the amplitude spectrum, we have no information about its variation within the interval  $dt$ .

The filters used in the ChISS system are chosen to optimize the trade-off between time and frequency. Zapolsky used frequency bands of width  $df$  that are just half the center frequency  $f_c$  of each filter (see Figure 1). They allow measurement of spectral amplitude for time intervals of duration  $2/f_c$  in each case (that is, for each filter), and enable an optimized description of the frequency content of the seismic signal as a function of time.

Four civilian ChISS recording sites were established by the Soviet Union in the region surrounding the Semipalatinsk test site (Figure 2). The components of a ChISS system are the seismometer, calibration device, amplifier, filter bank and galvanometer along with a photo-paper recording device. Instrument calibration was accomplished in the following manner. Each seismometer had an excitation coil with a separate magnet to input the calibration signal. The frequency of the calibration electric signal was slowly decreased in time from the high end of the highest frequency filter to the low end of the lowest frequency filter. The shape of the response to this signal on the seismogram exactly corresponds to the frequency response of the seismometer-filter-galvanometer system. The impulse response consists of 1.5-2 periods (3-4 extrema). Such a short transition guarantees minimal distortion of the initial seismic signal and stabilizes the envelope shape. Filters used in ChISS systems are characterized by the low and high band limits (at 0.7 maximum magnification),  $f_1$  and  $f_2$ , the central frequency,  $f_c$ , the absolute band width,  $df=f_2-f_1$ , and the relative band width,  $(f_2-f_1)/f_c$ .

The ChISS filter parameters are shown in Tables 1 and 2. Parameters were changed in September 1973 when the system was improved to include two sets of filters for independent short-period (ShP) and long-period (LP) seismometers, as well as independent systems of calibration and recording. The LP and ShP ChISS instruments employ Soviet SKD and SKM seismometers, respectively. Two identical ChISS filters, with central frequency 0.62 Hz, are output from both systems. The calibration signal was recorded daily on each ShP ChISS seismogram and once a week on LP ChISS seismograms. Responses for the ShP system are plotted in Figure 1. Examples of LP system seismograms from the ChISS station at Zerenda (ZRN) are given in Figure 3.

**Table 1.** Early ChISS parameters.

<b>f1-f2 (Hz)</b>	<b>fc (Hz)</b>	<b>Width</b>
0.27-0.40	0.32	0.4
0.54-0.84	0.67	0.45
1.1-1.7	1.36	0.45
2.3-3.6	2.9	0.45
4.6-7.1	5.7	0.45
9.2-14	11.3	0.45

**Table 2.** Standard ChISS parameters.

LP/ShP	f1-f2 (Hz)	fc (Hz)	Width
LP	0.05-0.1	0.07	0.7
LP	0.1-0.2	0.14	0.7
LP	0.2-0.4	0.28	0.5
LP	0.5-0.8	0.62	0.5
ShP	0.5-0.8	0.62	0.5
ShP	1.0-1.6	1.25	0.5
ShP	2.0-3.2	2.5	0.5
ShP	4.0-6.4	5.0	0.5
ShP	8.0-13.0	10.0	0.5

**2. Explosion Data**

The Talgar (TLG) ChISS station began operating in September 1961. It recorded almost all Soviet underground nuclear tests (UNTs) from the Semipalatinsk test site (STS), including the first two STS UNTs on Oct. 11, 1961, and Feb. 2, 1962, until the final tests in 1989.

For this study, we manually measured coda envelopes of 178 TLG ChISS records of 124 UNTs (nm/s) and entered the data into electronic form. More than 500 coda envelopes were analyzed from channels between 0.08 Hz and 5 Hz. Further details of the coda measurements can be found in our previous contribution (Rautian et al., 2004). In addition, we measured ChISS peak amplitudes for regional phases from 226 UNTs at the four ChISS stations, on multiple band channels, including two gain levels for certain records, and entered into electronic form. The measured phases were Pn, P2 (secondary Pn arrival), Pg, Sn, Li, Lg1, Lg2, Lg3 (various Lg peaks) and Rg, and we recovered 1753, 1439, 1469, 1430, 91, 1305, 1368, 1265, and 542 measurements for each phase, respectively, totaling 10,662 measurements overall. We also obtained measurements for a small number of chemical explosions and for the March 20, 1976, Semipalatinsk earthquake.

**3. ChISS Measurement**

To manually obtain the coda envelope from a photo paper record, one must choose each individual moment of time to measure. We choose measurement times such that monotonically decreasing amplitudes are obtained. Strict adherence to this rule enhances repeatability, which we have verified by comparing measurements obtained independently by two analysts. Further testing has shown that measurements from the ShP and LP systems in the common, 0.62 Hz, channel are the same.

The accuracy of manual measurements of ChISS envelopes depends on amplitude. The accuracy is lower for small amplitudes (below 1-2 mm) and large amplitudes (over 50-70 mm). We estimate that amplitudes less than 1 mm can be measured with error on the order of the amplitude itself. Therefore we eliminate all data below this level. The difficulty with large amplitudes is that waveforms from neighboring channels can overlap. Channels are recorded side by side and are separated by 70 mm; thus, amplitudes larger than 40-50 mm overlap. From our experience, measurement quality depends on brightness of the record. We keep the large amplitudes in our data set, which allows future decisions on their use on a case-by-case basis. This decision can be made comparing with smaller amplitude envelopes as the coda shapes are expected to be the same.

Occasionally, errors result from mistakes in measuring calibration levels. In such cases, both coda and phase amplitudes have the same discrepancy for that channel. This cannot be seen in individual envelopes, but is revealed in the spectra of individual events and in correlations between amplitude and magnitude. Such comparisons have been made to control the quality of the ChISS data sets.

**4. Integration into Coda Processing**

Talgar ChISS coda have been integrated into coda processing at LANL by applying ChISS filter bands (Tables 1 and 2) to digital data from central and east Asia, including digital seismograms from the Borovoye archive, STsR-TSG recording system (Kim and Ekstrom, 1996). Talgar envelopes were used in their raw form, under the assumption that differences in measuring envelopes manually and automatically would be consistent and would then

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be absorbed in frequency dependent site terms. To evaluate the Talgar ChISS coda results, we compared path-corrected coda amplitudes with common events recorded at Borovoye (Figure 4). Results show offsets that we attribute to measurement method (Figure 5), and show scatter that is very tight (standard deviation of differences less than 0.2, often less than 0.1). These levels compare favorably with those observed between modern digital stations (standard deviation 0.1 or less). The Talgar ChISS results can be used in yield calibration studies.

### **5. Phase Amplitude Data**

We have completed and quality controlled lists of amplitudes for regional phases for Semipalatinsk explosions recorded at four ChISS stations. Sample spectra for a variety of phases are shown in Figure 6 for a number of events that include the first and second Soviet underground tests, October 11, 1961, and February 2, 1962, respectively. We also show comparisons between spectra of events from the same adits (Figure 7). These comparisons will help us understand effects of near source damage on regional signals (these show very little effect) and, in the absence of such effects, will give us bounds on repeatability, after possible source scaling effects are accounted for. Discriminant ratios can also be studied using these data and an example of the behavior of cross-phase discriminants with frequency is shown in Figure 8. Finally, variation of discriminants with shot location and emplacement conditions can be studied. We show the variation of P2/Pn ratios, a measure of P complexity, in Figure 9, demonstrating marked differences between the Balapan and Degelen source regions, as well as coherent variations across the Degelen area. We suspect these variations are due to wave propagation effects.

### **CONCLUSIONS AND RECOMMENDATIONS**

We have manually measured coda envelopes from Talgar ChISS analog records for 124 STS explosions that occurred between 1961 and 1988. These data have been used to study the composition of the coda for the STS-Talgar path, define coda limits, estimate coda attenuation and construct a scaling law of explosion spectra (see previous year's contribution: Rautian et al., 2004). The coda data have been integrated into LANL coda calibration procedures. The ChISS data have been tested for consistency with existing Borovoye digital data from events recorded in common, and are suitable for use in yield calibration work. Phase amplitude measurements for Semipalatinsk explosions have also been collected, entered, and quality controlled. Examples of spectra are given, including spectra for events in the same adits. These data will be useful for studying variations in discriminant ratios that might result from shot point location or emplacement conditions. The distribution of a P complexity measurement for Talgar shows strong shot location dependence, thought to result from a wave propagation effect.

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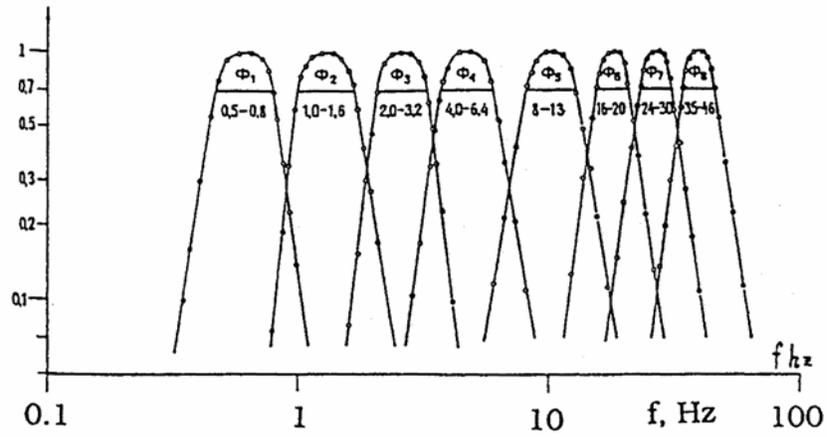


Figure 1. Short period ChISS response.

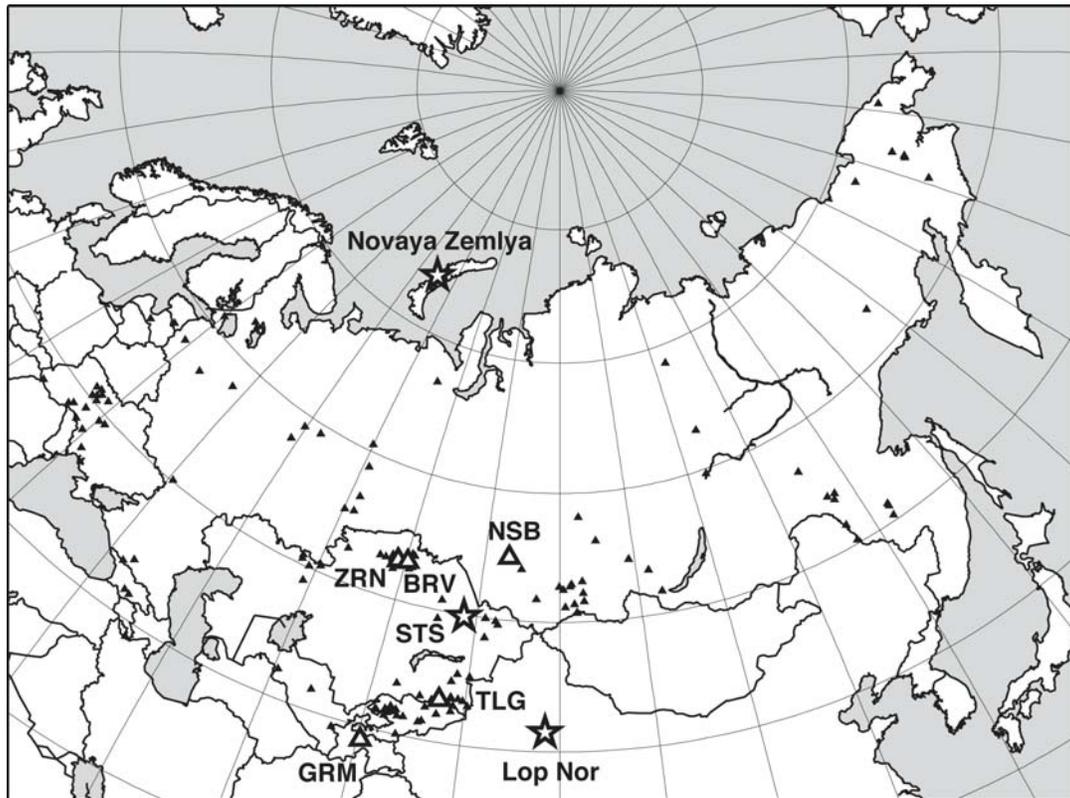


Figure 2. Map of Soviet stations and Asia test sites. Four ChISS stations and the Borovoye site are represented by large triangles, other Complex Seismological Expedition stations, by small triangles. Test sites are represented by stars.

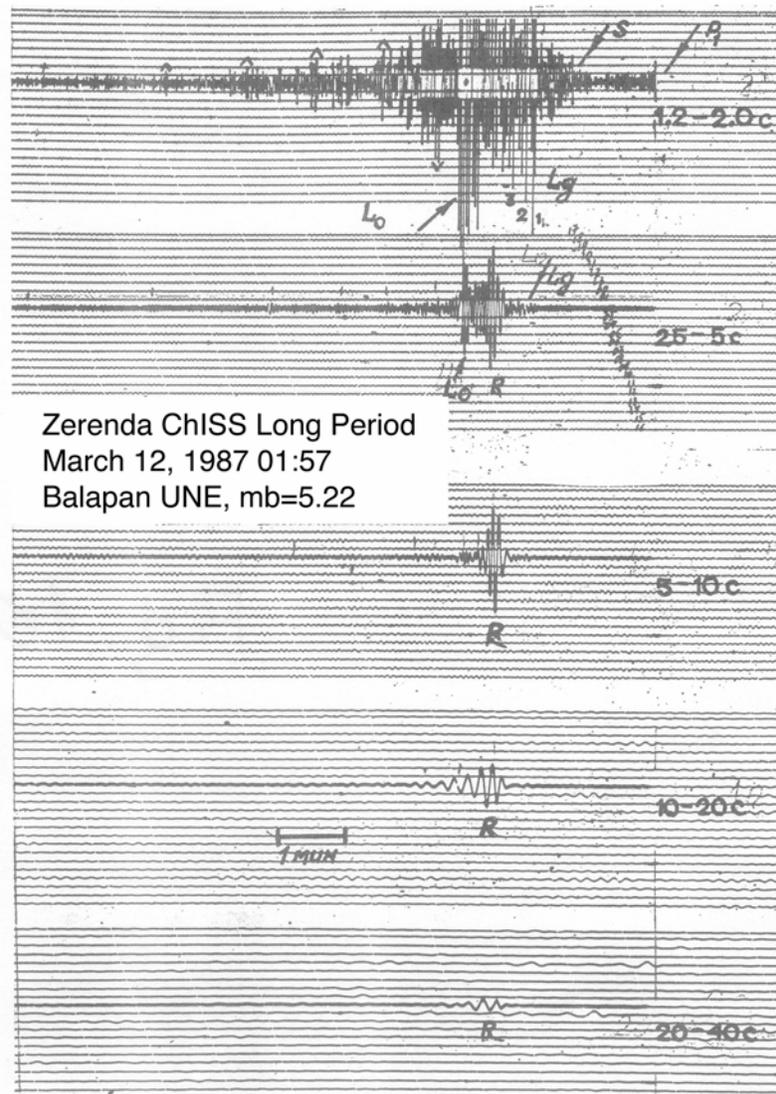


Figure 3. Long period ChISS seismograms from Zerenda. Time runs right to left.

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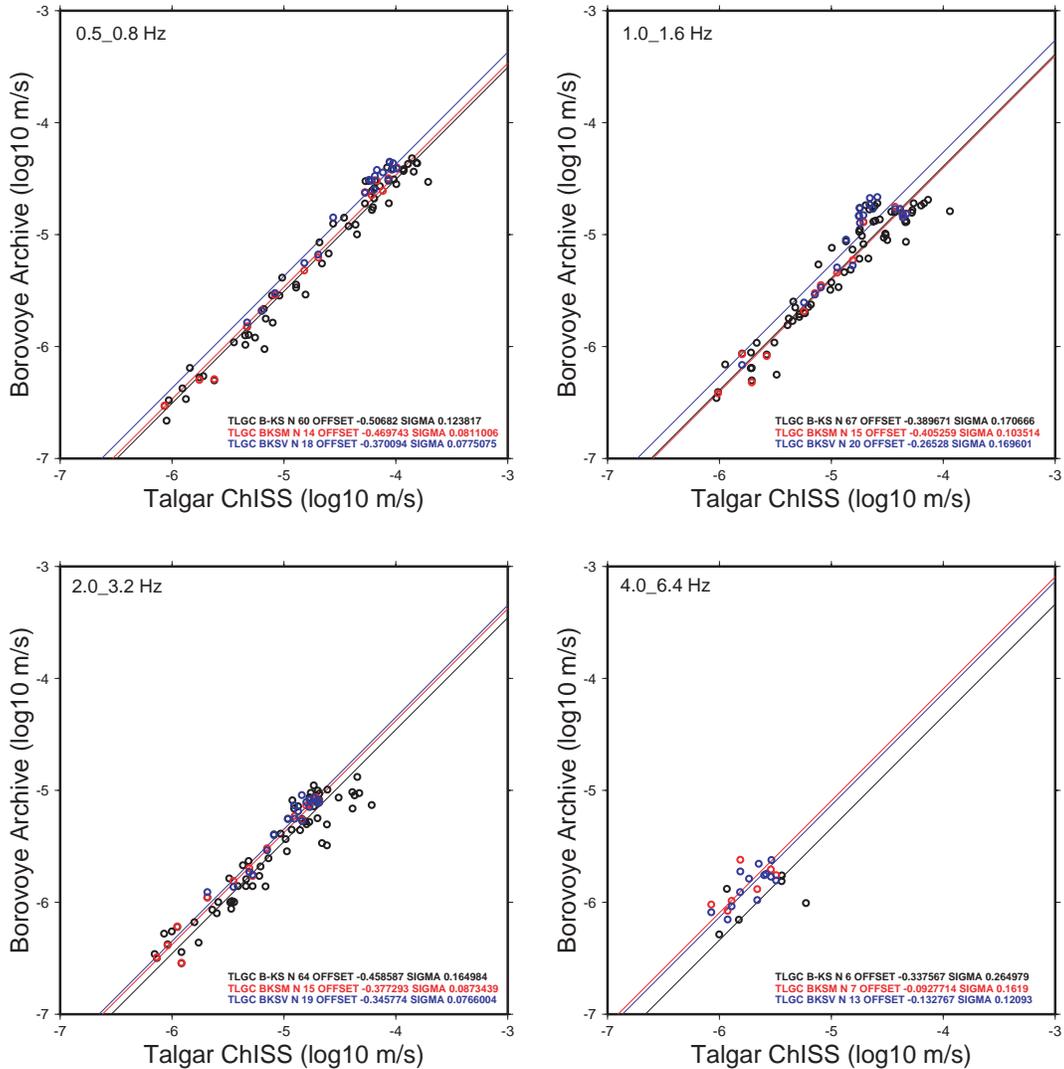


Figure 4. Comparison of path-corrected spectra between Talgar ChISS and Borovoye Archive stations.

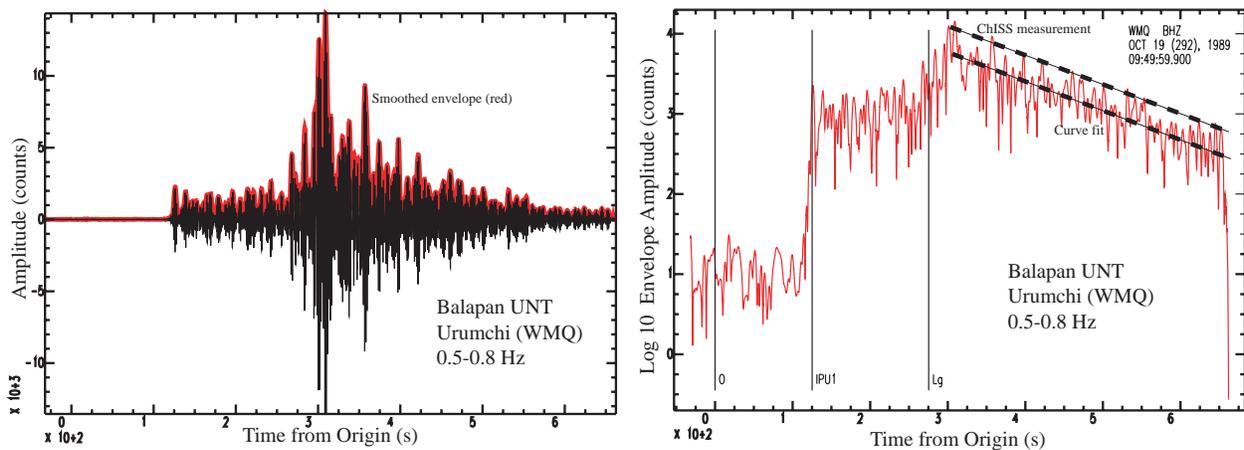


Figure 5. Example of offset resulting from ChISS measurement technique. This offset is absorbed in the site term when integrated into magnitude-yield processing for Asia. The calculation was performed in counts.

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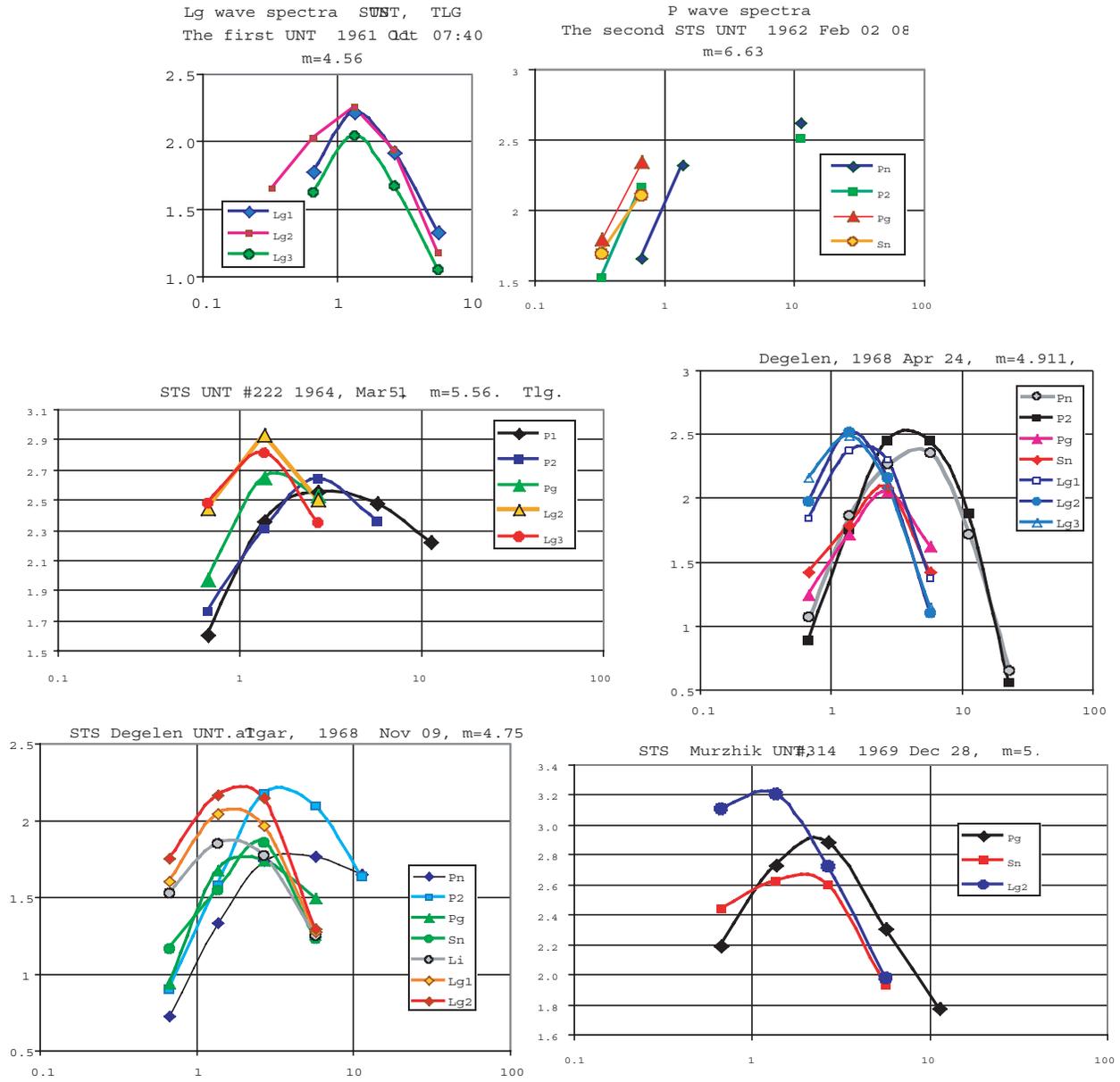


Figure 6. Examples of ChISS spectra (nm/s) for regional phases. Frequency in Hz.

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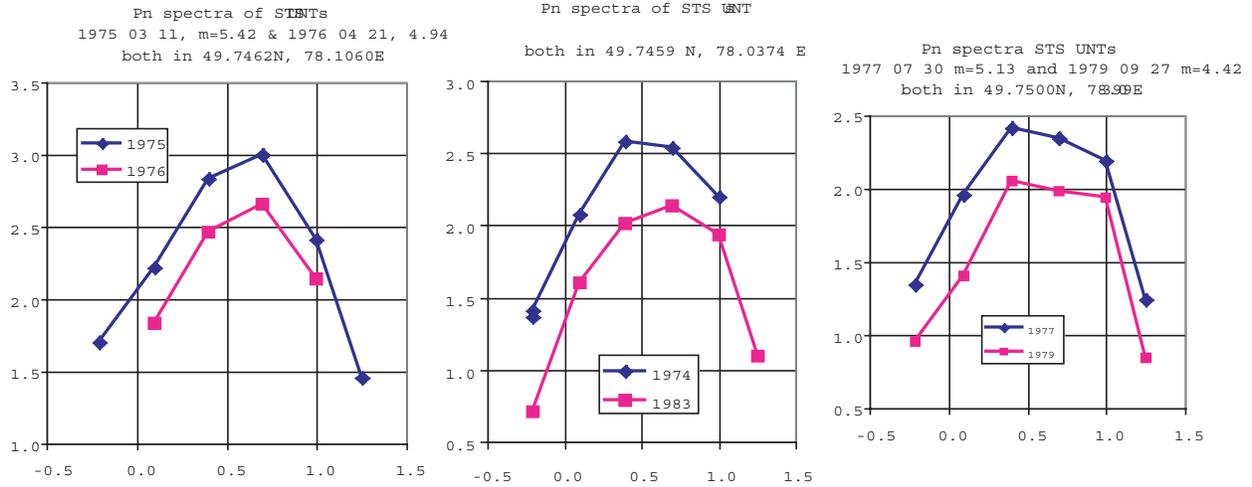


Figure 7. Examples of ChISS spectra (nm/s) for events in the same adit. Log10 frequency (Hz) is shown.

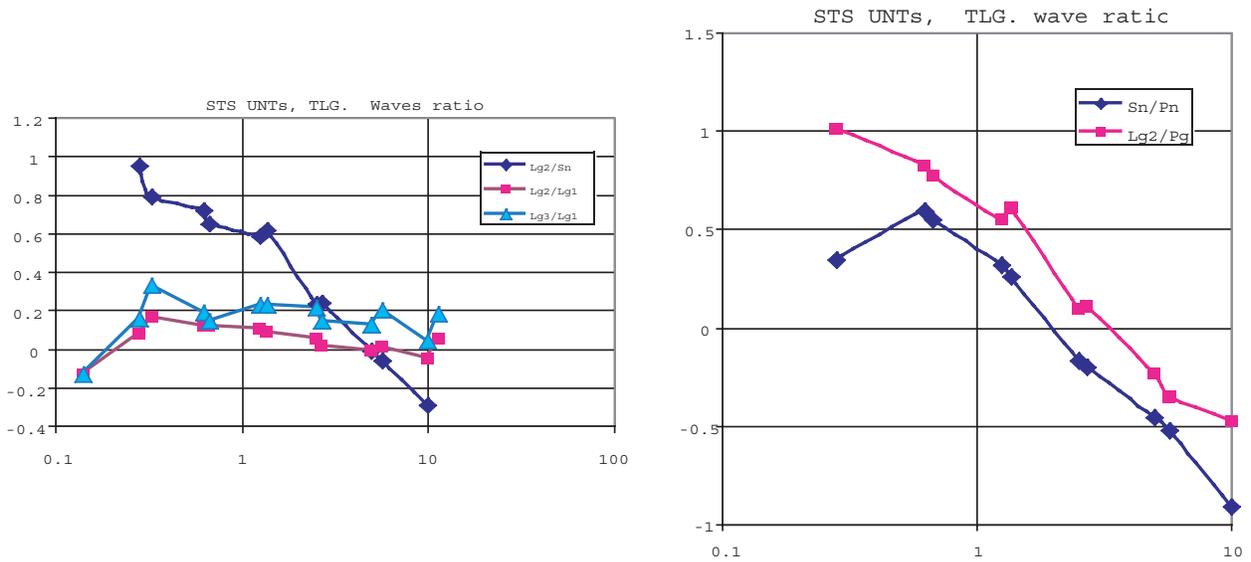


Figure 8. Spectral ratios versus frequency (Hz) for Semipalatinsk events.

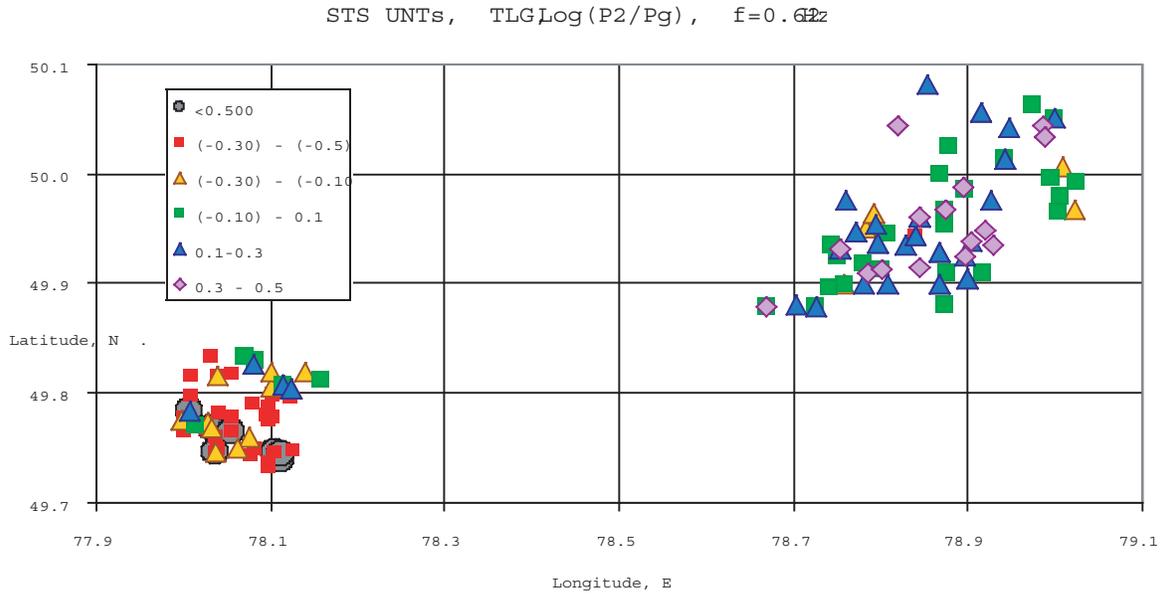


Figure 9. Geographical variation of the P2/Pg phase ratio for Balapan and Degelen events.